UNDULATOR AND PHOTON SPECTRUM AT DSR

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abstract

An undulator, which is inserted in DSR, is designed for high-resolution X ray spectroscopy experiment proposed in RIBF project at RIKEN. The undulator covers the energy range of 10 - 2000 eV of X ray using tunability of the K number and the electron beam energy in DSR. The photon spectrum from the undulator under low-emittance operation mode of DSR is calculated. The photon flux density reaches about 10^{18} (photons/s mrad^2 0.1%b.w.) and the photon flux is about 10^{15} (photons /s 0.1%b.w.) along the electron beam axis. The X ray beam line, which is located close to colliding section in DSR, is also designed.

1. INTRODUCTION

A high-resolution X ray spectroscopy experiment on the RI beam at DSR (Double Storage Rings) is proposed in RIBF (Radioactive Isotope Beam Factory) project at RIKEN [1,2]. In this experiment, we measure precisely isotope shifts and hyperfine structures in atomic transitions of highly-charged redioactive isotopes, which are produced with a projectile fragment separator using heavy-ion beam from SRC (Super-conducting Ring Cyclotron). From the measurements, we can derive systematically the mean-square nuclear charge radii and electromagnetic moments.

The Li-like charge state (Z-Q=3) is the most suitable for this experiment. It has the strong E1 transition, so-called D1 transition, from the ground state $2S_{1/2}$ to the first excited $2P_{1/2}$ state. The X ray energy range of 30 - 800 eV is required to excite the D1 transition of the Li-like ions of radioactive isotopes with Z = 40 - 92. The energy resolution of X ray ($\Delta E_x/E_x$) is required to be better than 2×10^{-4} to resolve the isotope shift in the D1 transition. One more requirement is that the photon flux of the X ray is as large as possible. In this paper, design and computer study on the undulator as a source of the X ray and the photon flux are described.

2. LOW-EMITTANCE ELECTRON BEAM

We have to provide intense and high quality X ray. The synchrotron radiation from the stored electron beam in DSR can be used for this purpose. The undulator is the best tool as the source of X ray. The X ray energy from the undurator depends on the electron beam energy. Wide range tunability of electron beam energy is required to cover the energy range of X ray described above. The electron beam is accelerated up to 300 MeV with a liniac and re accelerated up to 2.5 GeV with a BSR (Booster Synchrotron Ring), then it is injected into DSR. It means that we can choose any energy from 0.3 to 2.5 GeV. The quality of the electron beam are also important to make high-quality X ray. Especially, the quality strongly depends on the emittance of the electron beam. In DSR, the DBA lattice is adopted to get low-emittance electron beam and not only electron beam but also heavy ion beam have to be stored. There are three operation mode in DSR: low-emittance electron beam, large-emittance electron beam, and heavy ion operation modes. Details of the lattice of DSR and the operation modes are described in Ref. [3]. Here, we show the specifications of the electron beam under low-emittance operation mode of DSR (Table 1).

Other important things on the electron beam for the undulator are follows: The electron beam has thedispersion free and small beam size at the undulator section. The change of beam size should be as small as

Table 1. Specifications of low-emittance electron beam in DSR.

Electron beam energy (GeV)	0.3 - 2.5			
Maximum averaged current (A)	0.5			
Maximum number of stored electron	2.59×10^{12}			
Revolution frequency (MHz)	1.159			
Harmonics	432			
Electron energy (GeV)	1.0	1.5	2.0	2.5
Energy loss (keV/turn)	8.9	48.2	152.3	371.7
Emittance (nmrad) X	1.37	3.08	5.47	8.54
Y	4.08	9.18	16.3	25.5
Energy spread ($\Delta E/E$)	2.73×10^{-4}	4.11×10^{-4}	5.48×10^{-4}	6.80×10^{-4}
Bunch length (cm)	0.135	0.231	0.357	0.502
Dumping time (sec)X	0.183	0.054	0.023	0.012
Y	0.182	0.054	0.023	0.012
E	0.090	0.027	0.011	0.006
Quantum lifetime (sec)	3.54×10^{71}	1.08×10^{71}	4.44×10^{70}	2.28×10^{70}
Toushek lifetime (sec)	9.6×10^{4}	8.1×10^{3}	1.4×10^{4}	3.0×10^{4}

possible over the undulator length. According to design using the DBA lattice [3], the dispersion is completely suppressed in this section. The betatron amplitude in the undulator section is about 5 m and nearly constant at any point in the section using triplet Q lenses at both side of the section. Then the size of the electron beam in the undulator section is about σ_x/σ_y = 80/140 μm at 1.0 GeV.

3. DESIGN OF UNDULATOR

The undulator has been designed by considering the X ray energy, intensity and insertion space in the ring. In DSR, we have 6.5-m length straight section close to the colliding point for insertion devises (see ref. [3]). In this space, we can put 6-m length undulator and small compensators are also put at both side of the undulator.

Figure 1 shows schematically the one of the colliding section of DSR. X ray beam system consists of the undulator, X ray spectrometer, and X ray detector. The X ray spectrometer is used to make energy resolution higher and put in between vertically bending magnets at colliding section. The X ray extracted from the spectrometer is injected again into another ring, in which RI beam is stored, and collided with the RI beam with the angle of 0 or π rad. Resonance fluorescence X ray from the RI is detected. The distance between the undulator and the vertically bending magnet is about 8.4 m; about 21.1-m space is in between the bending magnets; and total length from undulator and the detector is about 38 m.

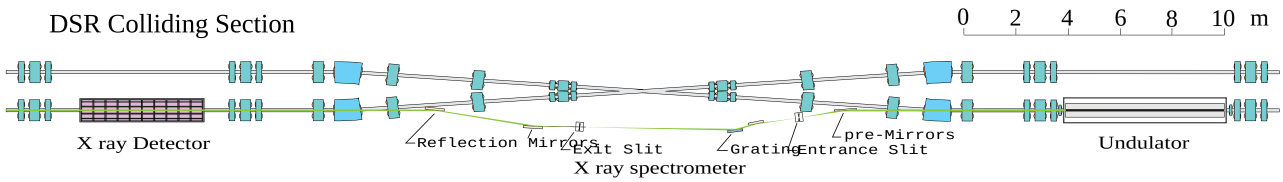

Fig. 1 Colliding section and the undulator in DSR.

The maximum photon flux density along electron beam axis for n-th harmonic radiation from the undulator is given by:

$$\left(\frac{d^3N}{dt\, d\lambda\, d\Omega}\right) = 4.5\mathrm{x}10^4\, \gamma^2\, N_p{}^2\, F_n(K)$$
$$\times \left[\left\{1+\left(\frac{\sigma_{x'}}{\sigma_U}\right)^2\right\}\left\{1+\left(\frac{\sigma_{y'}}{\sigma_U}\right)^2\right\}\right]^{-\frac{1}{2}}, \quad (1)$$

(photons/s mrad^2 mA 0.1%b.w.)

where γ is Lorenz factor, N_p the number of periods, σ_U natural angular spread of X ray, $\sigma_{x'}$ and $\sigma_{y'}$ angular spreads of electron beam in x and y directions, and $F_n(K)$ is expressed using Bessel functions as:

$$F_n(K)=\frac{n^2K^2}{(1+K^2/2)^2}\left[J_{(n-1)/2}\left(\frac{nK^2/4}{1+K^2/2}\right) - J_{(n+1)/2}\left(\frac{nK^2/4}{1+K^2/2}\right)\right]^2. \quad (2)$$

This factor has the maximum value at K number close to unity for the case of first harmonic radiation (n=1). There is a relation between K number and wavelength λ of X ray for the first harmonic radiation along electron beam axis as:

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right), \quad (3)$$

where λ_u is the length of one period. Figure 2 shows the relation between photon flux density and the X ray energy for the case of several λ_u values at K=1.0 when the electron beam energy changes from 0.3 to 2.5 GeV. The requited X ray energy can be covered with λ_u of 2.0 - 4.0 cm. When we take the medium value of λ_u = 3.0 cm, the influence of the tunability of K number is shown in Fig. 3. In the case of larger K value than 2.0, the required energy range cannot be covered and there is not so much change on the photon flux density. Therefore, we took

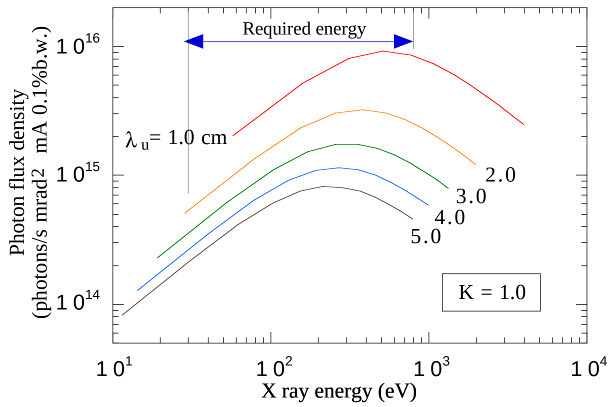

Fig. 2. Relation between the photon flux density and X ray energy at K=1.0.

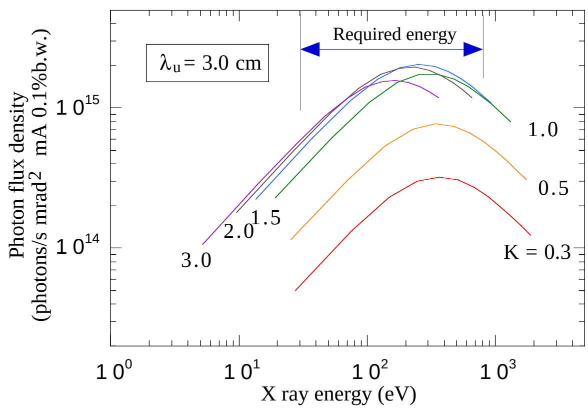

Fig. 3. Relation between the photon flux density and X ray energy at λu=3.0 cm.

3.0 cm as λ_u and tunability of the K value of 0.3-2.0. In this case, the gap width between magnets is changed from 2.9 to 1.1 cm, which is determined using K number and the magnetic field strength due to the permanent magnets. Parameters of the undulator are listed in Table 2. This undulator should be in vacuum type because minimum gap width is about 1 cm. It is not so difficult to insert the beam transport tube in between. But we need larger physical aperture because we have to store not only low-emittance electron beam but also the heavy ion beam and the electron beam for e-HI collision experiment which have much lager emittance.

Table 2. Parameters of undulator.

Length (m)	6.0
Length of a period (cm)	3.0
Number of periods	200
K value	0.3 - 2.0
Gap width (cm)	1.1 - 2.9
Magnetization (T)	1.3 (at pole tip)

4. PHOTON SPECTRUM

Equation (1) gives the muximum value of n-th harmonic radiation. To get whole spectrum of emitted X ray from the undulator, the numerical calculations have been done by considering influences of higher order harmonic radiations (up to n=5) and using electron beam parameters calculated above. Figure 4 shows the photon flux density for several electron energy. The electron beam current is assumed to be maximum value of 0.5 A and the K value is fixed to be unity. In this calculation, it is found that the optimum electron beam energy is 1.2 GeV to get maximum photon flux with fixed K value. The energy resolution of the X ray with lower energy of electron beam is much better than that with higher energy electron beam. The maximum photon flux density is about 10^{18} (photons/s mrad^2 0.1%b.w.). The qualities of the X ray emitted from the undulator are shown in Table 3.

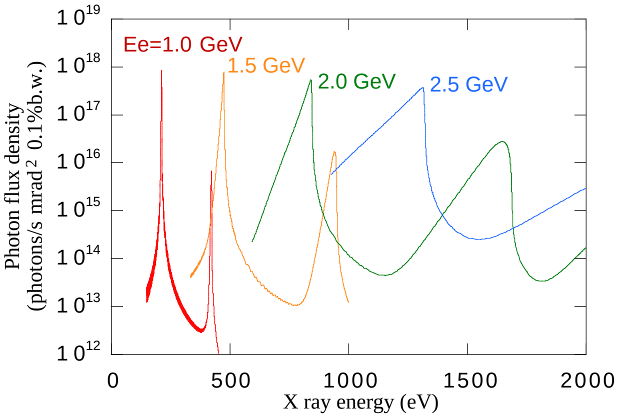

Fig. 4. Photon flux density at K=1.0

Table 3. Qualities of X ray from the undulator with K=1.0.

Electron energy (GeV)	1.0	1.5	2.0	2.5
X ray beam size (μm)	83.8	124.1	165.1	206.2
	143.6	214.5	285.8	357.2
Angular spread (μrad)	35.4	32.4	36.5	43.1
	42.4	47.7	59.2	72.5
X ray energy (eV)	211.0	474.8	844.1	1318.9
Radiation power (kW)	0.214	0.523	0.965	1.509
Photon flux density (photons/smdar^{2}0.1%b.w.)	8.58×10^{17}	7.68×10^{17}	5.33×10^{17}	3.68×10^{17}
Photon flux (photons/s 0.1%b.w.)	1.29×10^{15}	1.19×10^{15}	1.15×10^{15}	1.15×10^{15}
Brilliance (photons/smrad^{2}mm^{2}0.1%b.w.)	1.14×10^{19}	4.59×10^{18}	1.80×10^{18}	8.00×10^{17}

5. X RAY BEAM LINE

Photon flux along the beam axis is nearly constants (about 10^{15} photons/s 0.1%b.w.) for every electron beam energy. These photons are injected into X ray spectrometer. As seen in Fig.1, it consists of a pre-mirror, an entrance slit, a movable mirror, a grating, an exit slit, and two reflection mirrors. This type of spectrometer is based on the constant length spherical grating monochrometer (CL-SGM). The pre-mirror makes focus on the entrance slit, and the position of both slits are fixed. The movable mirror and the grating are moved so as to keep the light pass length between two slits and the direction of the extracted X ray. Then more two mirror are needed to put the light again on the beam axis. The X ray beam size at the detector position can be made to be the same size of RI beam of about 3 mm in diameter using focusing mirror like troidal mirror as the reflection mirrors. This spectrometer has not yet optimized and should have the resolution of about 10^{-4} to satisfy the requirement. This resolution can be achieved as shown in Ref [4]. The transmission rate of this spectrometer should be more than 1 %, then we can get X ray yield of about 10^{12} (photons/s 0.01%b.w.) for the spectroscopy experiment.

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